

ORIGINAL

Application Based on

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ORGANIC ELEMENT FOR ELECTROLUMINESCENT DEVICES

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ORGANIC ELEMENT FOR ELECTROLUMINESCENT DEVICES

FIELD OF THE INVENTION

This invention relates to an organic light emitting diode (OLED) electroluminescent (EL) device comprising a light-emitting layer containing an organometallic complex that can provide desirable electroluminescent properties.

BACKGROUND OF THE INVENTION

While organic electroluminescent (EL) devices have been known for over two decades, their performance limitations have represented a barrier to many desirable applications. In simplest form, an organic EL device is comprised of an anode for hole injection, a cathode for electron injection, and an organic medium sandwiched between these electrodes to support charge recombination that yields emission of light. These devices are also commonly referred to as organic light-emitting diodes, or OLEDs. Representative of earlier organic EL devices are Gurnee et al. U.S. Pat. No. 3,172,862, issued Mar. 9, 1965; Gurnee U.S. Pat. No. 3,173,050, issued Mar. 9, 1965; Dresner, "Double Injection Electroluminescence in Anthracene", RCA Review, Vol. 30, pp. 322-334, 1969; and Dresner U.S. Pat. No. 3,710,167, issued Jan. 9, 1973. The organic layers in these devices, usually composed of a polycyclic aromatic hydrocarbon, were very thick (much greater than 1 μm). Consequently, operating voltages were very high, often $>100\text{V}$.

More recent organic EL devices include an organic EL element consisting of extremely thin layers (e.g. $<1.0\ \mu\text{m}$) between the anode and the cathode. Herein, the term "organic EL element" encompasses the layers between the anode and cathode. Reducing the thickness lowered the resistance of the organic layer and has enabled devices that operate much lower voltage. In a basic two-layer EL device structure, described first in US 4,356,429, one organic layer of the EL element adjacent to the anode is specifically chosen to transport holes, therefore, it is referred to as the hole-transporting layer, and the other organic layer is specifically chosen to transport electrons, referred to as the electron-transporting

layer. Recombination of the injected holes and electrons within the organic EL element results in efficient electroluminescence.

There have also been proposed three-layer organic EL devices that contain an organic light-emitting layer (LEL) between the hole-transporting layer and electron-transporting layer, such as that disclosed by Tang et al [*J. Applied Physics*, Vol. 65, Pages 3610-3616, 1989]. The light-emitting layer commonly consists of a host material doped with a guest material, otherwise known as a dopant. Still further, there has been proposed in US 4,769,292 a four-layer EL element comprising a hole-injecting layer (HIL), a hole-transporting layer (HTL), a light-emitting layer (LEL) and an electron transport/injection layer (ETL). These structures have resulted in improved device efficiency.

Many emitting materials that have been described as useful in an OLED device emit light from their excited singlet state by fluorescence. The excited singlet state is created when excitons formed in an OLED device transfer their energy to the excited state of the dopant. However, it is generally believed that only 25% of the excitons created in an EL device are singlet excitons. The remaining excitons are triplet, which cannot readily transfer their energy to the singlet excited state of a dopant. This results in a large loss in efficiency since 75% of the excitons are not used in the light emission process.

Triplet excitons can transfer their energy to a dopant if it has a triplet excited state that is low enough in energy. If the triplet state of the dopant is emissive it can produce light by phosphorescence, wherein phosphorescence is a luminescence involving a change of spin state between the excited state and the ground state. In many cases singlet excitons can also transfer their energy to lowest singlet excited state of the same dopant. The singlet excited state can often relax, by an intersystem crossing process, to the emissive triplet excited state. Thus, it is possible, by the proper choice of host and dopant, to collect energy from both the singlet and triplet excitons created in an OLED device and to produce a very efficient phosphorescent emission.

One class of useful phosphorescent materials are transition metal complexes having a triplet excited state. For example, *fac*-tris(2-phenylpyridinato-

N,C^{2'})iridium(III) (Ir(ppy)₃) strongly emits green light from a triplet excited state owing to the large spin-orbit coupling of the heavy atom and to the lowest excited state which is a charge transfer state having a Laporte allowed (orbital symmetry) transition to the ground state (K.A. King, P.J. Spellane, and R.J. Watts, *J. Amer. Chem. Soc.*, **107**, 1431 (1985), M.G. Colombo, T.C. Brunold, T. Reidener, H.U. Gudel, M. Fortsch, and H.-B. Burgi, *Inorg. Chem.*, **33**, 545 (1994)). Small-molecule, vacuum-deposited OLEDs having high efficiency have also been demonstrated with Ir(ppy)₃ as the phosphorescent material and 4,4'-N,N'-dicarbazole-biphenyl (CBP) as the host (M.A. Baldo, S. Lamansky, P.E. Burrows, M.E. Thompson, S.R. Forrest, *Appl. Phys. Lett.*, **75**, 4 (1999), T. Tsutsui, M.-J. Yang, M. Yabito, K. Nakamura, T. Watanabe, T. Tsuji, Y. Fukuda, T. Wakimoto, S. Miyaguchi, *Jpn. J. Appl. Phys.*, **38**, L1502 (1999)).

Another class of phosphorescent materials include compounds having interactions between atoms having d¹⁰ electron configuration, such as Au₂(dppm)Cl₂ (dppm = bis(diphenylphosphino)methane) (Y. Ma et al, *Appl. Phys. Lett.*, **74**, 1361 (1998)). Still other examples of useful phosphorescent materials include coordination complexes of the trivalent lanthanides such as Tb³⁺ and Eu³⁺ (J. Kido et al, *Appl. Phys. Lett.*, **65**, 2124 (1994)). While these latter phosphorescent compounds do not necessarily have triplets as the lowest excited states, their optical transitions do involve a change in spin state of 1 and thereby can harvest the triplet excitons in OLED devices.

Notwithstanding these developments, there remains a need for new organometallic materials that will function as phosphorescent emitters. M. E. Thompson and co-workers have reported on the synthesis and characterization of a number of iridium complexes (*J. Amer. Chem. Soc.*, **125**, 7377 (2003)). Many of the phenylpyridyl-based complexes were intensely luminescent at room temperature. In contrast, the phenylpyrazolyl-based compounds, such as, tris(1-phenylpyrazolato-N,C^{2'}) iridium(III) either did not phosphoresce, or were very weak emitters, at room temperature.

Phenylpyrazolyl-based organometallic compounds are also described in JP 2003109758 A2, JP 2003142265 A2, US 2002134984 A1, and US

2002117662A1. US 20030175553 A1 describes the use of fac-tris(1-phenylpyrazolato-N,C 2)iridium(III) (Irppz) in an electron/exciton blocking layer. In this case, the material is not an emissive dopant but is used to prevent the movement of electrons or excitons from the luminescent layer into the hole-transporting layer.

It is a problem to be solved to provide new phosphorescent emitting materials that emit useful light.

SUMMARY OF THE INVENTION

The invention provides an electroluminescent device comprising a light-emitting layer including a light emitting material that contains an organometallic complex comprising (1) a metal selected from the group consisting of Ir, Rh, Os, Pt, and Pd and (2) a diazole group ligand wherein the ligand has a fused aromatic ring group including a nitrogen of the diazole as a bridgehead nitrogen. The invention also provides a display or area lighting device employing the electroluminescent device and a process for emitting light using the device.

The device emits light through phosphorescent emission.

BRIEF DESCRIPTION OF THE DRAWINGS

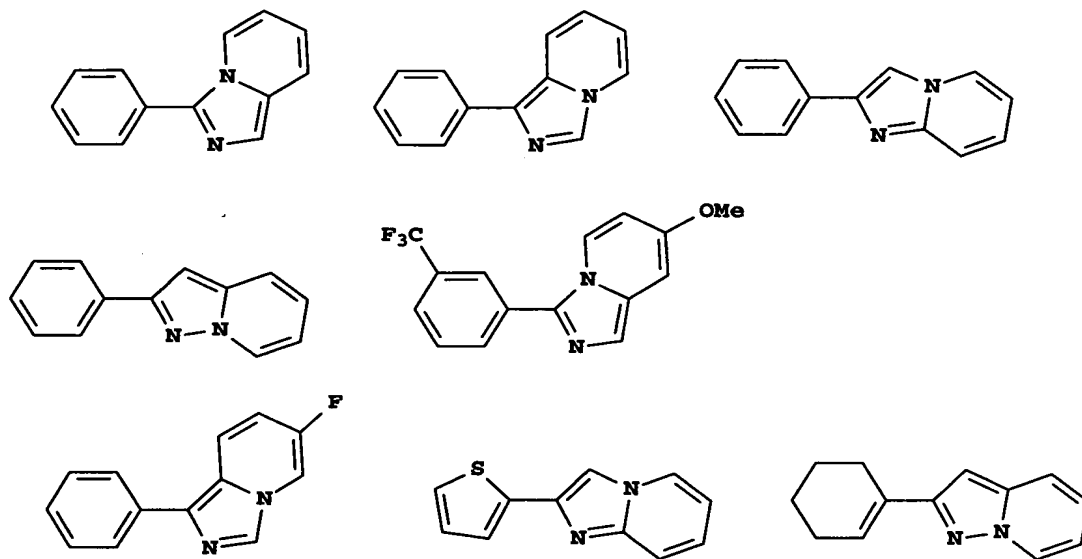
FIG. 1 shows a cross-section of a typical OLED device in which this invention may be used.

DETAILED DESCRIPTION OF THE INVENTION

The invention is summarized above. The organometallic complex comprises a metal selected from the group consisting of Ir, Rh, Os, Pt, and Pd and a diazole group ligand wherein the ligand has a fused aromatic ring group including a nitrogen of the diazole as a bridgehead nitrogen.

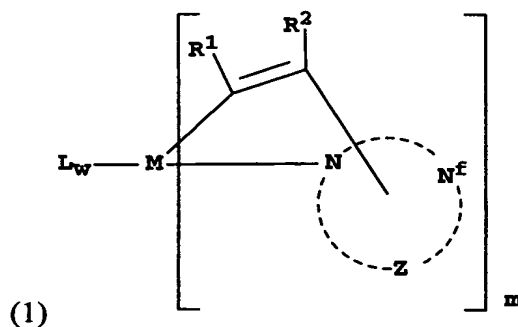
A diazole compound has a five-membered unsaturated ring containing two nitrogen atoms. Suitably the diazole ring is fused with at least one aromatic ring. It is desirable that one of the nitrogen atoms in the diazole ring be a bridgehead nitrogen at the junction with the fused ring. It is further desirable that the diazole ring be further substituted with a substituent that has at least one

double bond. Even more desirable, the double bond is part of a five or six-membered aromatic ring. Suitably the double bond forms an additional bond to the metal. Illustrative examples of diazole compounds are shown below.



5

In one desirable embodiment, the organometallic complex can be represented by Formula (1).



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In Formula (1), Z represents the atoms necessary to complete a diazole ring group that is fused with at least one aromatic ring group. For example, Z may represent the atoms necessary to complete an imidazopyridine ring group or a pyrazolopyridine ring group.

N^f represents a nitrogen atom at a bridgehead position between the diazole ring group and the fused aromatic ring group. In one suitable embodiment, N^f is not adjacent to the other nitrogen of the diazole ring.

M is a coordinated metal selected from the group consisting of Ir, Rh, Os, Pt, and Pd. In one suitable embodiment, M represents Ir or Rh, and more desirably M represents Ir.

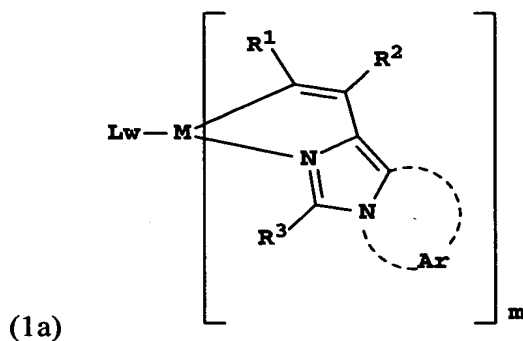
m is 1, 2 or 3 when M is Ir or Rh and m is 1 or 2 when M is Pt, Pd, or Os.

w is 0- 4 as necessary in order to satisfy a total of 6 coordination sites when M is Ir, Os, or Rh, and w is 0- 2 as necessary in order to satisfy 4 coordination sites when M is Pt or Pd.

L represents an independently selected ligand group. The ligand is chosen so that it can complex to the metal. For example, L can represent cyanide or a halogen, such as chloride. Desirably, L represents a bidentate ligand. For example, L can represent a carbonyl-substituted group such as an acetylacetonate group, a hexafluoroacetylacetonate group, or a salicylaldehyde group. L can also represent an acid derivative of formula $R^aCO_2^-$, wherein R^a represents an aryl group, such as phenyl or tolyl group, or an alkyl group, such as methyl or butyl group. Examples of desirable acid derivatives are picolinic acid and 3-bromopicolinic acid. L can also represent an alkoxide of formula R^aO^- , wherein R^a is as defined above, for example, R^aO^- can represent a phenoxide group.

One useful embodiment of the organometallic complex of Formula (1) is represented by Formula (1a):

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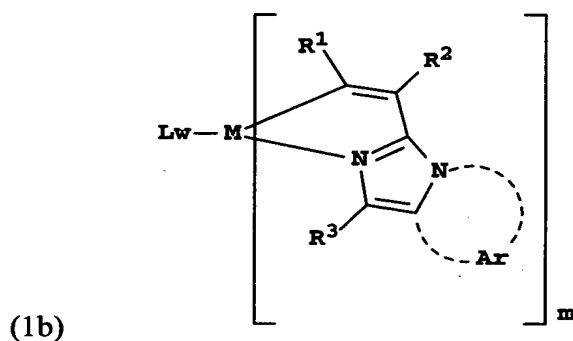


In Formula (1a), M, L, w, m, R¹, R² are as defined previously.

R³ represents hydrogen or a substituent. Examples of suitable
 5 substituents are groups such as an alkyl group, for example a methyl group or a
 trifluoromethyl group and an aryl group such as a phenyl group, or tolyl group.

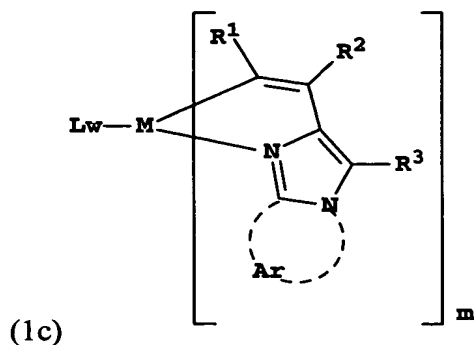
Ar represents the atoms necessary to form an aromatic ring group,
 such as a pyridine ring group or pyrrole ring group, a quinoline ring group, an
 isoquinoline ring group, a pyrimidine ring group, a pyrazine ring group, or a
 10 triazine ring group, and Ar may have additional fused rings.

In another useful embodiment of the invention the organometallic
 complex of Formula (1) is represented by Formula (1b):



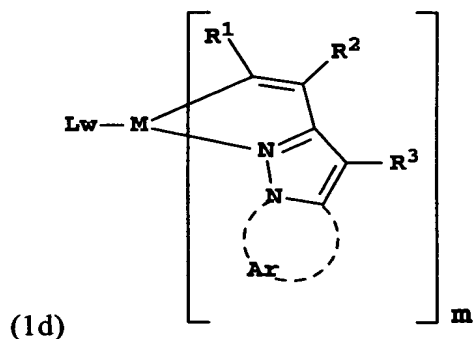
15 In Formula (1b), M, L, w, m, R¹, R², R³, and Ar are as defined
 previously.

In another suitable embodiment of the invention the organometallic
 complex of Formula (1) is represented by Formula (1c):



In Formula (1c), M, L, w, m, R¹, R², R³, and Ar are as defined previously.

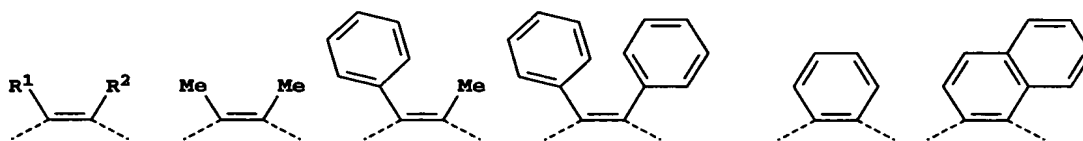
In another suitable embodiment of the invention the organometallic complex of Formula (1) is represented by Formula (1d):



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In Formula (1d), M, L, w, m, R¹, R², R³ and Ar are defined previously.

R¹ and R² represent substituent groups, provided that R¹ and R² may form a ring. Examples of R¹ and R² include aromatic groups such as phenyl, and tolyl groups and alkyl groups such as methyl and ethyl groups. In one desirable embodiment, R¹ and R² represent atoms that join together to form an aromatic ring, such as a benzene ring group. Illustrative examples of R¹ and R² are shown below. R¹ and R² may be chosen so as to fuse with the diazole ring group.



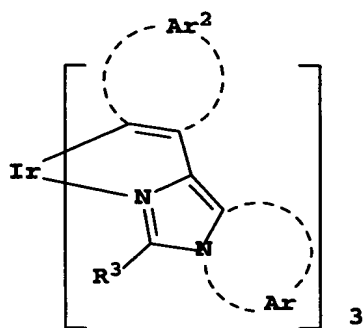
In one preferred embodiment, the organometallic compound of the invention is represented by Formula (1), wherein: w is 0, m is 3, and M represents Ir, and R¹ and R² represent the atoms necessary to form a six-membered aromatic ring group.

Suitably, the light-emitting layer of the device comprises a host and one or more dopants where the dopant(s) is present in an amount of up to 15 wt % of the host, more typically from 0.1-10.0 wt % and often from 2.0-10.0 wt % of the host. At least one dopant is suitably a complex comprising a ring system of Formula (1).

Desirable hosts are capable of forming a continuous film and the host is selected so as to have a high level of energy transfer from the host to the dopant material. Examples of desirable hosts are 4,4'-N,N'-dicarbazole-biphenyl (CBP), 2,2'-dimethyl-4,4'-N,N'-dicarbazole-biphenyl, and 1,3-(N,N'-dicarbazole)benzene.

In one useful embodiment the multilayer electroluminescent device contains a hole-blocking layer located between the light-emitting layer and the electron-transporting layer and preferably adjacent to the light-emitting layer. This layer can increase the efficiency of the device. Examples of useful hole-blocking materials are bis(2-methyl-quinolinolate)(4-phenylphenolate)Al (Balq) and 2,9-dimethyl-4,7-diphenyl-phenanthroline (bathocuproine, BCP).

In another useful embodiment of the invention the organometallic complex of Formula (1) is represented by Formula (1e):

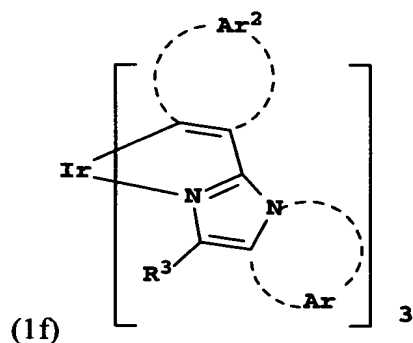


(1e)

In Formula (1e), Ar and R³ are defined previously.

5 Ar² represents the atoms necessary to form a five or six membered aromatic ring group, such as benzene group and naphthalene group. In one desirable embodiment, Ar and Ar² represent the atoms necessary to form a six-membered aromatic ring group, which may include additional fused rings.

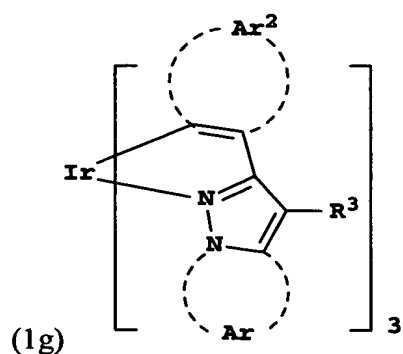
10 In another useful embodiment of the invention the organometallic complex of Formula (1) is represented by Formula (1f):



(1f)

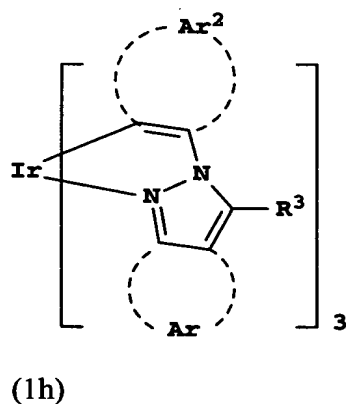
15 In Formula (1f), R³, Ar and Ar² are as defined previously. In one desirable embodiment, Ar and Ar² represent the atoms necessary to form six-membered aromatic ring groups which may include additional fused rings.

 In another useful embodiment of the invention the organometallic complex of Formula (1) is represented by Formula (1g):



In Formula (1g), R^3 , Ar and Ar^2 are as defined previously. In one desirable embodiment, Ar and Ar^2 represent the atoms necessary to form six-membered aromatic ring groups, which may include additional fused rings.

In another useful embodiment of the invention the organometallic complex of Formula (1) is represented by Formula (1h):



In Formula (1h), R^3 , Ar and Ar^2 are as defined previously. In one desirable embodiment, Ar and Ar^2 represent the atoms necessary to form six-membered aromatic ring groups which may include additional fused rings.

In one useful embodiment, at least one layer of the EL device, such as a LEL layer, comprises polymeric material. In another suitable embodiment, at least two layers of the OLED device comprise polymeric material.

In one desirable embodiment the EL device is part of a display device. In another suitable embodiment the EL device is part of an area lighting device.

Embodiments of the invention can provide advantageous features
5 such as operating efficiency, higher luminance, color hue, low drive voltage, and improved operating stability. Embodiments of the organometallic compounds useful in the invention can provide a wide range of hues including those useful in the emission of white light (directly or through filters).

In many cases the hue of an organometallic light-emitting
10 compound useful in the invention can be estimated by calculating its triplet state energy. The triplet state energy for a molecule is defined as the difference between the ground state energy ($E(\text{gs})$) of the molecule and the energy of the lowest triplet state ($E(\text{ts})$) of the molecule, both given in eV. These energies can be calculated using the B3LYP method as implemented in the Gaussian98 (Gaussian, Inc.,
15 Pittsburgh, PA) computer program. The basis set for use with the B3LYP method is defined as follows: MIDI! for all atoms for which MIDI! is defined, 6-31G* for all atoms defined in 6-31G* but not in MIDI!, and either the LACV3P or the LANL2DZ basis set and pseudopotential for atoms not defined in MIDI! or 6-31G*, with LACV3P being the preferred method. For any remaining atoms, any
20 published basis set and pseudopotential may be used. MIDI!, 6-31G* and LANL2DZ are used as implemented in the Gaussian98 computer code and LACV3P is used as implemented in the Jaguar 4.1 (Schrodinger, Inc., Portland Oregon) computer code. The energy of each state is computed at the minimum-energy geometry for that state. The difference in energy between the two states is
25 further modified by Equation 1 to give the triplet state energy ($E(\text{t})$):

$$E(\text{t}) = 0.84 * (E(\text{ts}) - E(\text{gs})) + 0.35.$$

For polymeric or oligomeric materials, it is sufficient to compute the triplet energy over a monomer or oligomer of sufficient size so that additional units do not substantially change the computed triplet energy.

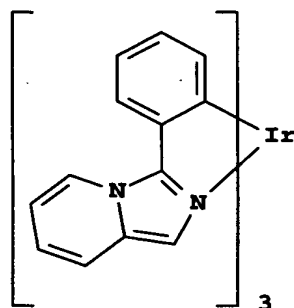
30 Synthesis of the emitting materials useful in the invention may be accomplished by preparing the organic ligand and then using a metal to complex

the ligand and form the organometallic compound. The synthesis of ligands useful in the invention may be accomplished by various methods found in the literature, for example, see T. Benincori, E. Brenna, F. Sannicolo, *J. Chem. Soc., Perkin Trans. 1*, 675 (1993), R. Tachikawa, S. Tanaka, A. Terada, Atsusuke, *Heterocycles*, **15**, 369 (1981), C. Enguehard, J. Renou, V. Collot, M. Hervet, S. Rault, A Gueiffier, *J. of Org. Chem.*, **65**, 6572 (2000) and R. Adams, J. Dix, *J. Amer. Chem. Soc.*, **80** 46 (1958).

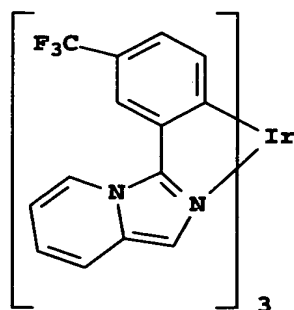
The organometallic complex useful in the invention may be synthesized from the prepared ligands by various literature methods. For example, see A. Tamayo, B. Alleyne, P. Djurovich, S. Lamansky, I. Tsyba, N. Ho, R. Bau, M. Thompson, *J. Amer. Chem. Soc.* **125**, 7377 (2003), H. Konno, Y. Sasaki, *Chem. Lett.*, **32**, 252 (2003), and V. Grushin, N. Hurren, D. LeCloux, W. Marshall, V. Petrov, and Y. Wang, *Chem. Comm.*, 1494 (2001).

Illustrative examples of complexes of Formula (1) useful in the present invention are the following:

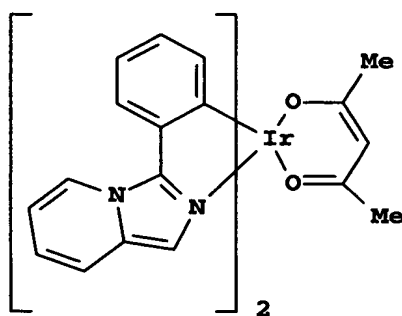
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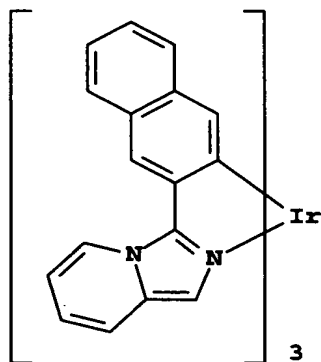
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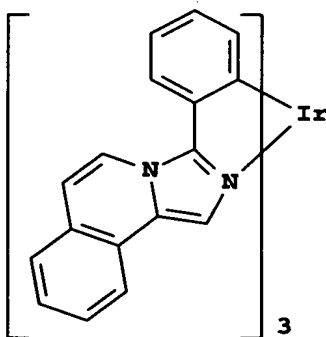
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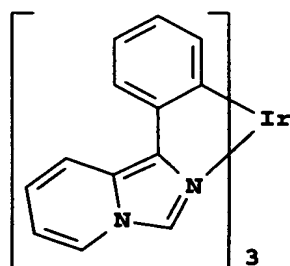
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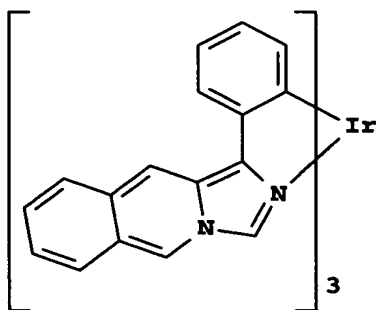
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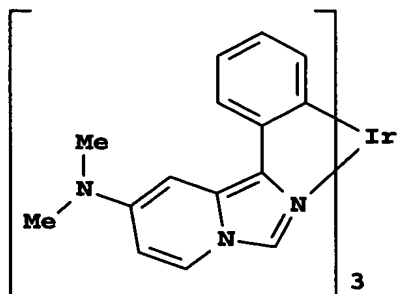
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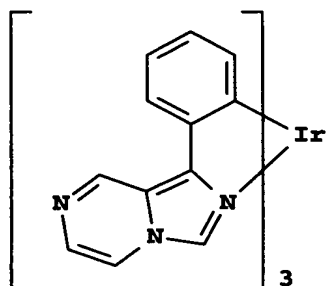
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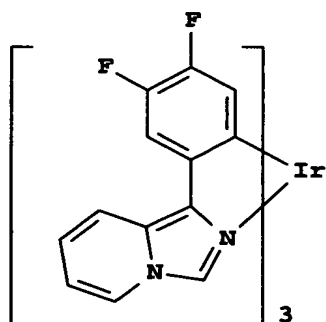
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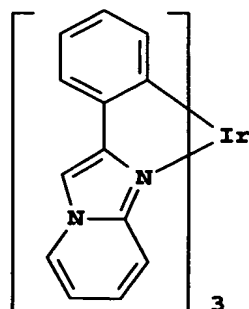
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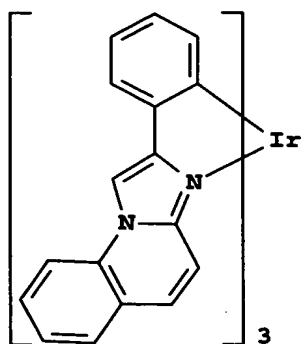
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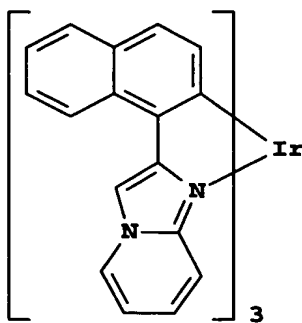
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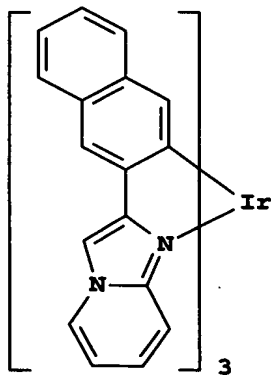
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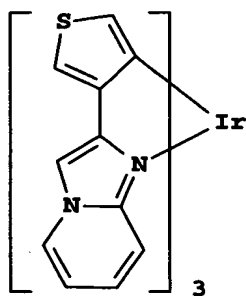
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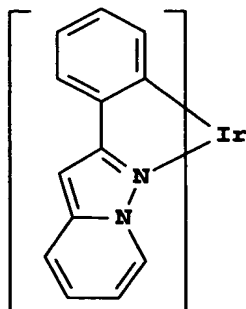
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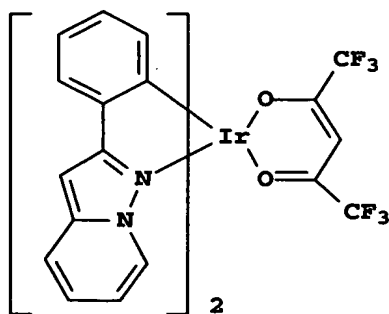
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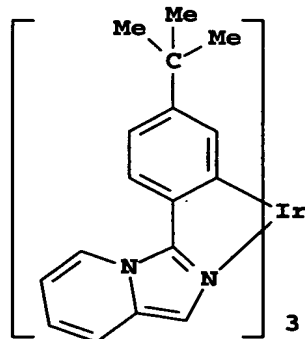
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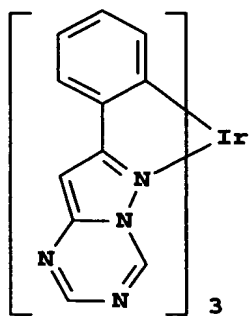
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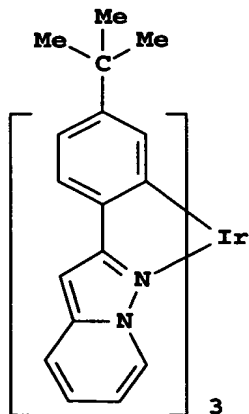
Inv-18



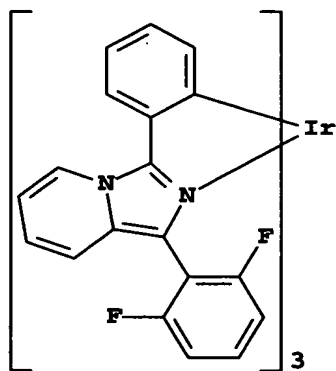
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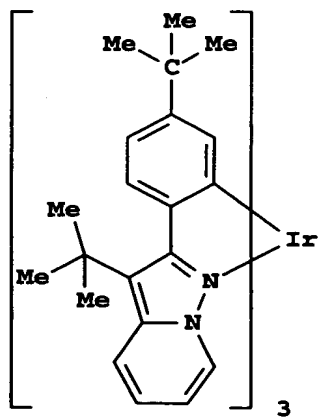
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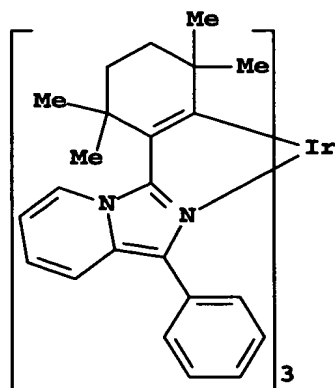
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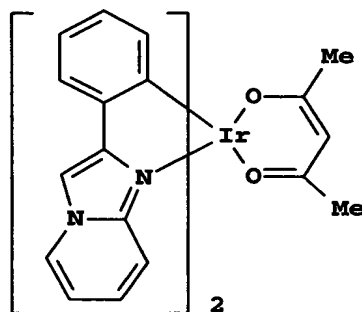
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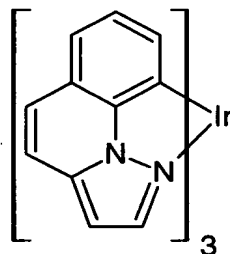
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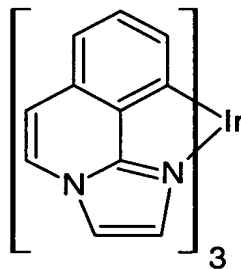
Inv-24



Inv-25



Inv-26



Unless otherwise specifically stated, use of the term "substituted" or "substituent" means any group or atom other than hydrogen. Unless otherwise provided, when a group (including a compound or complex) containing a substitutable hydrogen is referred to, it is also intended to encompass not only the unsubstituted form, but also form further substituted derivatives with any substituent group or groups as herein mentioned, so long as the substituent does

not destroy properties necessary for utility. Suitably, a substituent group may be halogen or may be bonded to the remainder of the molecule by an atom of carbon, silicon, oxygen, nitrogen, phosphorous, sulfur, selenium, or boron. The substituent may be, for example, halogen, such as chloro, bromo or fluoro; nitro; hydroxyl; cyano; carboxyl; or groups which may be further substituted, such as alkyl, including straight or branched chain or cyclic alkyl, such as methyl, trifluoromethyl, ethyl, t-butyl, 3-(2,4-di-t-pentylphenoxy) propyl, and tetradecyl; alkenyl, such as ethylene, 2-butene; alkoxy, such as methoxy, ethoxy, propoxy, butoxy, 2-methoxyethoxy, sec-butoxy, hexyloxy, 2-ethylhexyloxy, tetradecyloxy, 2-(2,4-di-t-pentylphenoxy)ethoxy, and 2-dodecyloxyethoxy; aryl such as phenyl, 4-t-butylphenyl, 2,4,6-trimethylphenyl, naphthyl; aryloxy, such as phenoxy, 2-methylphenoxy, alpha- or beta-naphthyloxy, and 4-tolyloxy; carbonamido, such as acetamido, benzamido, butyramido, tetradecanamido, alpha-(2,4-di-t-pentylphenoxy)acetamido, alpha-(2,4-di-t-pentylphenoxy)butyramido, alpha-(3-pentadecylphenoxy)-hexanamido, alpha-(4-hydroxy-3-t-butylphenoxy)-tetradecanamido, 2-oxo-pyrrolidin-1-yl, 2-oxo-5-tetradecylpyrrolin-1-yl, N-methyltetradecanamido, N-succinimido, N-phthalimido, 2,5-dioxo-1-oxazolidinyl, 3-dodecyl-2,5-dioxo-1-imidazolyl, and N-acetyl-N-dodecylamino, ethoxycarbonylamino, phenoxycarbonylamino, benzyloxycarbonylamino, hexadecyloxycarbonylamino, 2,4-di-t-butylphenoxycarbonylamino, phenylcarbonylamino, 2,5-(di-t-pentylphenyl)carbonylamino, p-dodecylphenylcarbonylamino, p-tolylcarbonylamino, N-methylureido, N,N-dimethylureido, N-methyl-N-dodecylureido, N-hexadecylureido, N,N-dioctadecylureido, N,N-dioctyl-N'-ethylureido, N-phenylureido, N,N-diphenylureido, N-phenyl-N-p-tolylureido, N-(m-hexadecylphenyl)ureido, N,N-(2,5-di-t-pentylphenyl)-N'-ethylureido, and t-butylcarbonamido; sulfonamido, such as methylsulfonamido, benzenesulfonamido, p-tolylsulfonamido, p-dodecylbenzenesulfonamido, N-methyltetradecylsulfonamido, N,N-dipropylsulfamoylamino, and hexadecylsulfonamido; sulfamoyl, such as N-methylsulfamoyl, N-ethylsulfamoyl, N,N-dipropylsulfamoyl, N-hexadecylsulfamoyl, N,N-dimethylsulfamoyl, N-[3-

(dodecyloxy)propyl]sulfamoyl, N-[4-(2,4-di-t-pentylphenoxy)butyl]sulfamoyl, N-methyl-N-tetradecylsulfamoyl, and N-dodecylsulfamoyl; carbamoyl, such as N-methylcarbamoyl, N,N-dibutylcarbamoyl, N-octadecylcarbamoyl, N-[4-(2,4-di-t-pentylphenoxy)butyl]carbamoyl, N-methyl-N-tetradecylcarbamoyl, and N,N-di-
5 dioctylcarbamoyl; acyl, such as acetyl, (2,4-di-t-amylphenoxy)acetyl, phenoxycarbonyl, p-dodecyloxyphenoxycarbonyl methoxycarbonyl, butoxycarbonyl, tetradecyloxycarbonyl, ethoxycarbonyl, benzyloxycarbonyl, 3-pentadecyloxycarbonyl, and dodecyloxycarbonyl; sulfonyl, such as methoxysulfonyl, octyloxysulfonyl, tetradecyloxysulfonyl, 2-
10 ethylhexyloxysulfonyl, phenoxysulfonyl, 2,4-di-t-pentylphenoxysulfonyl, methylsulfonyl, octylsulfonyl, 2-ethylhexylsulfonyl, dodecylsulfonyl, hexadecylsulfonyl, phenylsulfonyl, 4-nonylphenylsulfonyl, and p-tolylsulfonyl; sulfonyloxy, such as dodecylsulfonyloxy, and hexadecylsulfonyloxy; sulfinyl, such as methylsulfinyl, octylsulfinyl, 2-ethylhexylsulfinyl, dodecylsulfinyl,
15 hexadecylsulfinyl, phenylsulfinyl, 4-nonylphenylsulfinyl, and p-tolylsulfinyl; thio, such as ethylthio, octylthio, benzylthio, tetradecylthio, 2-(2,4-di-t-pentylphenoxy)ethylthio, phenylthio, 2-butoxy-5-t-octylphenylthio, and p-tolylthio; acyloxy, such as acetyloxy, benzoyloxy, octadecanoyloxy, p-dodecylamidobenzoyloxy, N-phenylcarbamoyloxy, N-ethylcarbamoyloxy, and
20 cyclohexylcarbamoyloxy; amine, such as phenylanilino, 2-chloroanilino, diethylamine, dodecylamine; imino, such as 1 (N-phenylimido)ethyl, N-succinimido or 3-benzylhydantoinyl; phosphate, such as dimethylphosphate and ethylbutylphosphate; phosphite, such as diethyl and dihexylphosphite; a heterocyclic group, a heterocyclic oxy group or a heterocyclic thio group, each of
25 which may be substituted and which contain a 3 to 7 membered heterocyclic ring composed of carbon atoms and at least one hetero atom selected from the group consisting of oxygen, nitrogen, sulfur, phosphorous, or boron. such as 2-furyl, 2-thienyl, 2-benzimidazolyloxy or 2-benzothiazolyloxy; quaternary ammonium, such as triethylammonium; quaternary phosphonium, such as triphenylphosphonium; and
30 silyloxy, such as trimethylsilyloxy.

If desired, the substituents may themselves be further substituted one or more times with the described substituent groups. The particular substituents used may be selected by those skilled in the art to attain the desired desirable properties for a specific application and can include, for example,
5 electron-withdrawing groups, electron-donating groups, and steric groups. When a molecule may have two or more substituents, the substituents may be joined together to form a ring such as a fused ring unless otherwise provided. Generally, the above groups and substituents thereof may include those having up to 48 carbon atoms, typically 1 to 36 carbon atoms and usually less than 24 carbon
10 atoms, but greater numbers are possible depending on the particular substituents selected.

Suitably, the light-emitting layer of the OLED device comprises a host material and one or more guest materials for emitting light. At least one of the guest materials is suitably a phosphorescent complex comprising a ring system of
15 Formula 1. The light-emitting guest material(s) is usually present in an amount less than the amount of host materials and is typically present in an amount of up to 15 wt % of the host, more typically from 0.1-10.0 wt % of the host. For convenience, the phosphorescent complex guest material may be referred to herein as a phosphorescent material. The phosphorescent material of Formula 1 is
20 preferably a low molecular weight compound, but it may also be an oligomer or a polymer having a main chain or a side chain of repeating units having the moiety represented by Formula 1. It may be provided as a discrete material dispersed in the host material, or it may be bonded in some way to the host material, for example, covalently bonded into a polymeric host.

25

Host Materials for Phosphorescent Materials

Suitable host materials should be selected so that the triplet exciton can be transferred efficiently from the host material to the phosphorescent material. For this transfer to occur, it is a highly desirable condition that the
30 excited state energy of the phosphorescent material be lower than the difference in energy between the lowest triplet state and the ground state of the host. However,

the band gap of the host should not be chosen so large as to cause an unacceptable increase in the drive voltage of the OLED. Suitable host materials are described in WO 00/70655 A2; 01/39234 A2; 01/ 93642 A1; 02/074015 A2; 02/15645 A1, and US 2002/0117662. Suitable hosts include certain aryl amines, triazoles, indoles
5 and carbazole compounds. Examples of desirable hosts are 4,4'-N,N'-dicarbazole-biphenyl (CBP), 2,2'-dimethyl-4,4'-N,N'-dicarbazole-biphenyl, *m*-(N,N'-dicarbazole)benzene, and poly(N-vinylcarbazole), including their derivatives.

Desirable host materials are capable of forming a continuous film. The light-emitting layer may contain more than one host material in order to
10 improve the device's film morphology, electrical properties, light emission efficiency, and lifetime. The light emitting layer may contain a first host material that has good hole-transporting properties, and a second host material that has good electron-transporting properties.

15 Other Phosphorescent Materials

Phosphorescent materials of Formula 1 may be used in combination with other phosphorescent materials, either in the same or different layers. Some other phosphorescent materials are described in WO 00/57676, WO 00/70655, WO 01/41512 A1, WO 02/15645 A1, US 2003/0017361 A1, WO
20 01/93642 A1, WO 01/39234 A2, US 6,458,475 B1, WO 02/071813 A1, US 6,573,651 B2, US 2002/0197511 A1, WO 02/074015 A2, US 6,451,455 B1, US 2003/ 0072964 A1, US 2003 / 0068528 A1, US 6,413,656 B1, US 6,515,298 B2, US 6,451,415 B1, US 6,097,147, US 2003/0124381 A1, US 2003/0059646 A1, US 2003/0054198 A1, EP 1 239 526 A2, EP 1 238 981 A2, EP 1 244 155 A2, US
25 2002/0100906 A1, US 2003 / 0068526 A1, US 2003/0068535 A1, JP 2003073387A, JP 2003 073388A, US 2003/0141809 A1, US 2003/0040627 A1, JP 2003059667A, JP 2003073665A, and US 2002/0121638 A1.

The emission wavelengths of cyclometallated Ir(III) complexes of the type IrL₃ and IrL₂L', such as the green-emitting *fac*-tris(2-phenylpyridinato-N,C^{2'})Iridium(III) and bis(2-phenylpyridinato-N,C^{2'})Iridium(III)(acetylacetonate)
30 may be shifted by substitution of electron donating or withdrawing groups at

appropriate positions on the cyclometallating ligand L, or by choice of different heterocycles for the cyclometallating ligand L. The emission wavelengths may also be shifted by choice of the ancillary ligand L'. Examples of red emitters are the bis(2-(2'-benzothienyl)pyridinato-N,C^{3'})Iridium(III)(acetylacetonate) and
5 tris(1-phenylisoquinolino-N,C^{2'})Iridium(III). A blue-emitting example is bis(2-(4,6-difluorophenyl)-pyridinato-N,C^{2'})Iridium(III)(picolinate).

Red electrophosphorescence has been reported, using bis(2-(2'-benzo[4,5-a]thienyl)pyridinato-N, C^{3'}) iridium (acetylacetonate) [Btp₂Ir(acac)] as the phosphorescent material (Adachi, C., Lamansky, S., Baldo, M. A., Kwong, R.
10 C., Thompson, M. E., and Forrest, S. R., *App. Phys. Lett.*, **78**, 1622-1624 (2001).

Other important phosphorescent materials include cyclometallated Pt(II) complexes such as cis-bis(2-phenylpyridinato-N,C^{2'})platinum(II), cis-bis(2-(2'-thienyl)pyridinato-N,C^{3'}) platinum(II), cis-bis(2-(2'-thienyl)quinolino-N,C^{5'}) platinum(II), or (2-(4,6-difluorophenyl)pyridinato-NC^{2'}) platinum (II)
15 acetylacetonate. Pt(II) porphyrin complexes such as 2,3,7,8,12,13,17,18-octaethyl-21H, 23H-porphine platinum(II) are also useful phosphorescent materials.

Still other examples of useful phosphorescent materials include coordination complexes of the trivalent lanthanides such as Tb³⁺ and Eu³⁺ (J. Kido et al, *Appl. Phys. Lett.*, **65**, 2124 (1994))

20

Blocking Layers

In addition to suitable hosts, an OLED device employing a phosphorescent material often requires at least one exciton- or hole- or electron-blocking layer to help confine the excitons or electron-hole recombination centers
25 to the light-emitting layer comprising the host and phosphorescent material. In one embodiment, such a blocking layer would be placed between the electron-transporting layer and the light-emitting layer – see Fig 1, layer 110. In this case, the ionization potential of the blocking layer should be such that there is an energy barrier for hole migration from the host into the electron-transporting layer, while
30 the electron affinity should be such that electrons pass more readily from the electron-transporting layer into the light-emitting layer comprising host and

phosphorescent material. It is further desired, but not absolutely required, that the triplet energy of the blocking material be greater than that of the phosphorescent material. Suitable hole-blocking materials are described in WO 00/70655A2 and WO 01/93642 A1. Two examples of useful materials are bathocuproine (BCP) and
5 bis(2-methyl-8-quinolinolato)(4-phenylphenolato)Aluminum(III) (BALQ). Metal complexes other than Balq are also known to block holes and excitons as described in US 2003/0068528. US 2003/0175553 A1 describes the use of fac-tris(1-phenylpyrazolato-N,C^{2'})iridium(III) (Irppz) in an electron/exciton blocking layer.

10 Embodiments of the invention can provide advantageous features such as operating efficiency, higher luminance, color hue, low drive voltage, and improved operating stability. Embodiments of the organometallic compounds useful in the invention can provide a wide range of hues including those useful in the emission of white light (directly or through filters to provide multicolor
15 displays).

General Device Architecture

The present invention can be employed in many OLED device configurations using small molecule materials, oligomeric materials, polymeric materials, or combinations thereof. These include very simple structures
20 comprising a single anode and cathode to more complex devices, such as passive matrix displays comprised of orthogonal arrays of anodes and cathodes to form pixels, and active-matrix displays where each pixel is controlled independently, for example, with thin film transistors (TFTs).

25 There are numerous configurations of the organic layers wherein the present invention can be successfully practiced. The essential requirements of an OLED are an anode, a cathode, and an organic light-emitting layer located between the anode and cathode. Additional layers may be employed as more fully described hereafter.

30 A typical structure, especially useful for of a small molecule device, is shown in FIG. 1 and is comprised of a substrate 101, an anode 103, a

hole-injecting layer **105**, a hole-transporting layer **107**, a light-emitting layer **109**, a hole- or exciton-blocking layer **110**, an electron-transporting layer **111**, and a cathode **113**. These layers are described in detail below. Note that the substrate may alternatively be located adjacent to the cathode, or the substrate may actually constitute the anode or cathode. The organic layers between the anode and cathode are conveniently referred to as the organic EL element. Also, the total combined thickness of the organic layers is desirably less than 500 nm.

The anode and cathode of the OLED are connected to a voltage/current source through electrical conductors. The OLED is operated by applying a potential between the anode and cathode such that the anode is at a more positive potential than the cathode. Holes are injected into the organic EL element from the anode and electrons are injected into the organic EL element at the cathode. Enhanced device stability can sometimes be achieved when the OLED is operated in an AC mode where, for some time period in the cycle, the potential bias is reversed and no current flows. An example of an AC driven OLED is described in US 5,552,678.

Substrate

The OLED device of this invention is typically provided over a supporting substrate **101** where either the cathode or anode can be in contact with the substrate. The electrode in contact with the substrate is conveniently referred to as the bottom electrode. Conventionally, the bottom electrode is the anode, but this invention is not limited to that configuration. The substrate can either be light transmissive or opaque, depending on the intended direction of light emission. The light transmissive property is desirable for viewing the EL emission through the substrate. Transparent glass or plastic is commonly employed in such cases. The substrate can be a complex structure comprising multiple layers of materials. This is typically the case for active matrix substrates wherein TFTs are provided below the OLED layers. It is still necessary that the substrate, at least in the emissive pixilated areas, be comprised of largely transparent materials such as glass or polymers. For applications where the EL emission is viewed through the top electrode, the transmissive characteristic of the bottom support is immaterial, and

therefore can be light transmissive, light absorbing or light reflective. Substrates for use in this case include, but are not limited to, glass, plastic, semiconductor materials, silicon, ceramics, and circuit board materials. Again, the substrate can be a complex structure comprising multiple layers of materials such as found in active matrix TFT designs. It is necessary to provide in these device configurations a light-transparent top electrode.

Anode

When the desired electroluminescent light emission (EL) is viewed through the anode, the anode should be transparent or substantially transparent to the emission of interest. Common transparent anode materials used in this invention are indium-tin oxide (ITO), indium-zinc oxide (IZO) and tin oxide, but other metal oxides can work including, but not limited to, aluminum- or indium-doped zinc oxide, magnesium-indium oxide, and nickel-tungsten oxide. In addition to these oxides, metal nitrides, such as gallium nitride, and metal selenides, such as zinc selenide, and metal sulfides, such as zinc sulfide, can be used as the anode. For applications where EL emission is viewed only through the cathode, the transmissive characteristics of the anode are immaterial and any conductive material can be used, transparent, opaque or reflective. Example conductors for this application include, but are not limited to, gold, iridium, molybdenum, palladium, and platinum. Typical anode materials, transmissive or otherwise, have a work function of 4.1 eV or greater. Desired anode materials are commonly deposited by any suitable means such as evaporation, sputtering, chemical vapor deposition, or electrochemical means. Anodes can be patterned using well-known photolithographic processes. Optionally, anodes may be polished prior to application of other layers to reduce surface roughness so as to minimize shorts or enhance reflectivity.

Cathode

When light emission is viewed solely through the anode, the cathode used in this invention can be comprised of nearly any conductive material. Desirable materials have good film-forming properties to ensure good contact with the underlying organic layer, promote electron injection at low voltage, and have

good stability. Useful cathode materials often contain a low work function metal (< 4.0 eV) or metal alloy. One useful cathode material is comprised of a Mg:Ag alloy wherein the percentage of silver is in the range of 1 to 20 %, as described in U.S. Patent No. 4,885,221. Another suitable class of cathode materials includes
5 bilayers comprising the cathode and a thin electron-injection layer (EIL) in contact with an organic layer (e.g., an electron transporting layer (ETL)) which is capped with a thicker layer of a conductive metal. Here, the EIL preferably includes a low work function metal or metal salt, and if so, the thicker capping layer does not need to have a low work function. One such cathode is comprised of a thin layer
10 of LiF followed by a thicker layer of Al as described in U.S. Patent No. 5,677,572. An ETL material doped with an alkali metal, for example, Li-doped Alq, is another example of a useful EIL. Other useful cathode material sets include, but are not limited to, those disclosed in U.S. Patent Nos. 5,059,861, 5,059,862, and 6,140,763.

15 When light emission is viewed through the cathode, the cathode must be transparent or nearly transparent. For such applications, metals must be thin or one must use transparent conductive oxides, or a combination of these materials. Optically transparent cathodes have been described in more detail in US 4,885,211, US 5,247,190, JP 3,234,963, US 5,703,436, US 5,608,287, US
20 5,837,391, US 5,677,572, US 5,776,622, US 5,776,623, US 5,714,838, US 5,969,474, US 5,739,545, US 5,981,306, US 6,137,223, US 6,140,763, US 6,172,459, EP 1 076 368, US 6,278,236, and US 6,284,3936. Cathode materials are typically deposited by any suitable method such as evaporation, sputtering, or chemical vapor deposition. When needed, patterning can be achieved through
25 many well known methods including, but not limited to, through-mask deposition, integral shadow masking as described in US 5,276,380 and EP 0 732 868, laser ablation, and selective chemical vapor deposition.

Hole-Injecting Layer (HIL)

A hole-injecting layer 105 may be provided between anode 103 and
30 hole-transporting layer 107. The hole-injecting material can serve to improve the film formation property of subsequent organic layers and to facilitate injection of

holes into the hole-transporting layer. Suitable materials for use in the hole-injecting layer include, but are not limited to, porphyrinic compounds as described in US 4,720,432, plasma-deposited fluorocarbon polymers as described in US 6,208,075, and some aromatic amines, for example, m-MTDATA (4,4',4"-tris[(3-methylphenyl)phenylamino]triphenylamine). Alternative hole-injecting materials reportedly useful in organic EL devices are described in EP 0 891 121 A1 and EP 1 029 909 A1.

Hole-Transporting Layer (HTL)

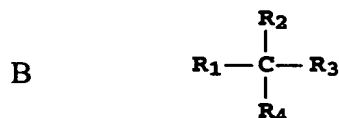
The hole-transporting layer 107 of the organic EL device contains at least one hole-transporting compound such as an aromatic tertiary amine, where the latter is understood to be a compound containing at least one trivalent nitrogen atom that is bonded only to carbon atoms, at least one of which is a member of an aromatic ring. In one form the aromatic tertiary amine can be an arylamine, such as a monoarylamine, diarylamine, triarylamine, or a polymeric arylamine. Exemplary monomeric triarylamine are illustrated by Klupfel et al. in US 3,180,730. Other suitable triarylamine substituted with one or more vinyl radicals and/or comprising at least one active hydrogen containing group are disclosed by Brantley et al. in US 3,567,450 and US 3,658,520.

A more preferred class of aromatic tertiary amines are those which include at least two aromatic tertiary amine moieties as described in US 4,720,432 and US 5,061,569. Such compounds include those represented by structural formula (A).



wherein Q₁ and Q₂ are independently selected aromatic tertiary amine moieties and G is a linking group such as an arylene, cycloalkylene, or alkylene group of a carbon to carbon bond. In one embodiment, at least one of Q₁ or Q₂ contains a polycyclic fused ring structure, e.g., a naphthalene. When G is an aryl group, it is conveniently a phenylene, biphenylene, or naphthalene moiety.

A useful class of triarylamines satisfying structural formula (A) and containing two triarylamine moieties is represented by structural formula (B):



where

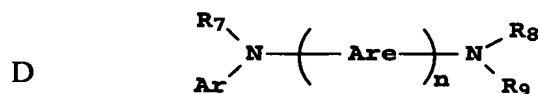
R₁ and R₂ each independently represents a hydrogen atom, an aryl group, or an alkyl group or R₁ and R₂ together represent the atoms completing a cycloalkyl group; and

R₃ and R₄ each independently represents an aryl group, which is in turn substituted with a diaryl substituted amino group, as indicated by structural formula (C):



wherein R₅ and R₆ are independently selected aryl groups. In one embodiment, at least one of R₅ or R₆ contains a polycyclic fused ring structure, e.g., a naphthalene.

Another class of aromatic tertiary amines are the tetraaryldiamines. Desirable tetraaryldiamines include two diarylamino groups, such as indicated by formula (C), linked through an arylene group. Useful tetraaryldiamines include those represented by formula (D).



wherein

each Are is an independently selected arylene group, such as a phenylene or anthracene moiety,

n is an integer of from 1 to 4, and

Ar, R₇, R₈, and R₉ are independently selected aryl groups.

In a typical embodiment, at least one of Ar, R₇, R₈, and R₉ is a polycyclic fused ring structure, e.g., a naphthalene

The various alkyl, alkylene, aryl, and arylene moieties of the foregoing structural formulae (A), (B), (C), (D), can each in turn be substituted. Typical substituents include alkyl groups, alkoxy groups, aryl groups, aryloxy groups, and halogen such as fluoride, chloride, and bromide. The various alkyl and alkylene moieties typically contain from about 1 to 6 carbon atoms. The cycloalkyl moieties can contain from 3 to about 10 carbon atoms, but typically contain five, six, or seven ring carbon atoms--e.g., cyclopentyl, cyclohexyl, and cycloheptyl ring structures. The aryl and arylene moieties are usually phenyl and phenylene moieties.

The hole-transporting layer can be formed of a single or a mixture of aromatic tertiary amine compounds. Specifically, one may employ a triarylamine, such as a triarylamine satisfying the formula (B), in combination with a tetraaryldiamine, such as indicated by formula (D). When a triarylamine is employed in combination with a tetraaryldiamine, the latter is positioned as a layer interposed between the triarylamine and the electron injecting and transporting layer. Illustrative of useful aromatic tertiary amines are the following:

1,1-Bis(4-di-*p*-tolylaminophenyl)cyclohexane

1,1-Bis(4-di-*p*-tolylaminophenyl)-4-phenylcyclohexane

N,N,N',N'-tetraphenyl-4,4'''-diamino-1,1':4',1'':4'',1'''-quaterphenyl

Bis(4-dimethylamino-2-methylphenyl)phenylmethane

1,4-bis[2-[4-[N,N-di(*p*-tolyl)amino]phenyl]vinyl]benzene (BDTAPVB)

N,N,N',N'-Tetra-*p*-tolyl-4,4'-diaminobiphenyl

N,N,N',N'-Tetraphenyl-4,4'-diaminobiphenyl

N,N,N',N'-tetra-1-naphthyl-4,4'-diaminobiphenyl

N,N,N',N'-tetra-2-naphthyl-4,4'-diaminobiphenyl

N-Phenylcarbazole

4,4'-Bis[N-(1-naphthyl)-N-phenylamino]biphenyl (NPB)

4,4'-Bis[N-(1-naphthyl)-N-(2-naphthyl)amino]biphenyl (TNB)

4,4'-Bis[N-(1-naphthyl)-N-phenylamino]*p*-terphenyl

4,4'-Bis[N-(2-naphthyl)-N-phenylamino]biphenyl

4,4'-Bis[N-(3-acenaphthenyl)-N-phenylamino]biphenyl

- 1,5-Bis[N-(1-naphthyl)-N-phenylamino]naphthalene
4,4'-Bis[N-(9-anthryl)-N-phenylamino]biphenyl
4,4'-Bis[N-(1-anthryl)-N-phenylamino]-*p*-terphenyl
4,4'-Bis[N-(2-phenanthryl)-N-phenylamino]biphenyl
5 4,4'-Bis[N-(8-fluoranthenyl)-N-phenylamino]biphenyl
4,4'-Bis[N-(2-pyrenyl)-N-phenylamino]biphenyl
4,4'-Bis[N-(2-naphthacenyl)-N-phenylamino]biphenyl
4,4'-Bis[N-(2-perylenyl)-N-phenylamino]biphenyl
4,4'-Bis[N-(1-coronenyl)-N-phenylamino]biphenyl
10 2,6-Bis(di-*p*-tolylamino)naphthalene
2,6-Bis[di-(1-naphthyl)amino]naphthalene
2,6-Bis[N-(1-naphthyl)-N-(2-naphthyl)amino]naphthalene
N,N,N',N'-Tetra(2-naphthyl)-4,4''-diamino-*p*-terphenyl
4,4'-Bis{N-phenyl-N-[4-(1-naphthyl)-phenyl]amino}biphenyl
15 2,6-Bis[N,N-di(2-naphthyl)amino]fluorene
4,4',4''-tris[(3-methylphenyl)phenylamino]triphenylamine (MTDATA)
4,4'-Bis[N-(3-methylphenyl)-N-phenylamino]biphenyl (TPD)

Another class of useful hole-transporting materials includes polycyclic aromatic compounds as described in EP 1 009 041. Tertiary aromatic amines with more than two amine groups may be used including oligomeric materials. In addition, polymeric hole-transporting materials can be used such as poly(N-vinylcarbazole) (PVK), polythiophenes, polypyrrole, polyaniline, and copolymers such as poly(3,4-ethylenedioxythiophene) / poly(4-styrenesulfonate) also called PEDOT/PSS.

25 Fluorescent Light-Emitting Materials and Layers (LEL)

In addition to the phosphorescent materials of this invention, other light emitting materials may be used in the OLED device, including fluorescent materials. Although the term "fluorescent" is commonly used to describe any light emitting material, in this case we are referring to a material that emits light from a singlet excited state. Fluorescent materials may be used in the same layer as the

30

phosphorescent material, in adjacent layers, in adjacent pixels, or any combination. Care must be taken not to select materials that will adversely affect the performance of the phosphorescent materials of this invention. One skilled in the art will understand that triplet excited state energies of materials in the same layer as the phosphorescent material or in an adjacent layer must be appropriately set so as to prevent unwanted quenching.

As more fully described in U.S. Patent Nos. 4,769,292 and 5,935,721, the light-emitting layer (LEL) of the organic EL element includes a luminescent fluorescent or phosphorescent material where electroluminescence is produced as a result of electron-hole pair recombination in this region. The light-emitting layer can be comprised of a single material, but more commonly consists of a host material doped with a guest emitting material or materials where light emission comes primarily from the emitting materials and can be of any color. The host materials in the light-emitting layer can be an electron-transporting material, as defined below, a hole-transporting material, as defined above, or another material or combination of materials that support hole-electron recombination. Fluorescent emitting materials are typically incorporated at 0.01 to 10 % by weight of the host material.

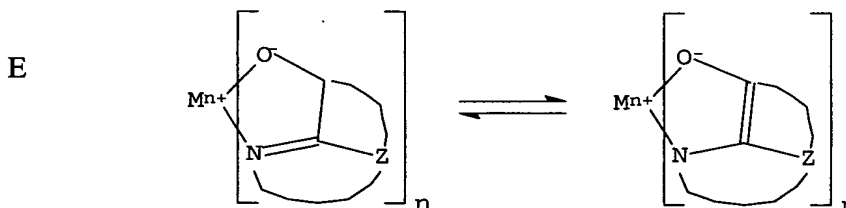
The host and emitting materials can be small non-polymeric molecules or polymeric materials such as polyfluorenes and polyvinylarylenes (e.g., poly(p-phenylenevinylene), PPV). In the case of polymers, small molecule emitting materials can be molecularly dispersed into a polymeric host, or the emitting materials can be added by copolymerizing a minor constituent into a host polymer. Host materials may be mixed together in order to improve film formation, electrical properties, light emission efficiency, lifetime, or manufacturability. The host may comprise a material that has good hole-transporting properties and a material that has good electron-transporting properties.

An important relationship for choosing a fluorescent dye as a guest emitting material is a comparison of the singlet excited state energies of the host and light-emitting material. For efficient energy transfer from the host to the

emitting material, a highly desirable condition is that the singlet excited state energy of the emitting material is lower than that of the host material.

Host and emitting materials known to be of use include, but are not limited to, those disclosed in US 4,768,292, US 5,141,671, US 5,150,006, US 5,151,629, US 5,405,709, US 5,484,922, US 5,593,788, US 5,645,948, US 5,683,823, US 5,755,999, US 5,928,802, US 5,935,720, US 5,935,721, and US 6,020,078.

Metal complexes of 8-hydroxyquinoline and similar derivatives (Formula E) constitute one class of useful host compounds capable of supporting electroluminescence, and are particularly suitable for light emission of wavelengths longer than 500 nm, e.g., green, yellow, orange, and red.



wherein

M represents a metal;

n is an integer of from 1 to 4; and

Z independently in each occurrence represents the atoms completing a nucleus having at least two fused aromatic rings.

From the foregoing it is apparent that the metal can be monovalent, divalent, trivalent, or tetravalent metal. The metal can, for example, be an alkali metal, such as lithium, sodium, or potassium; an alkaline earth metal, such as magnesium or calcium; an earth metal, such aluminum or gallium, or a transition metal such as zinc or zirconium. Generally any monovalent, divalent, trivalent, or tetravalent metal known to be a useful chelating metal can be employed.

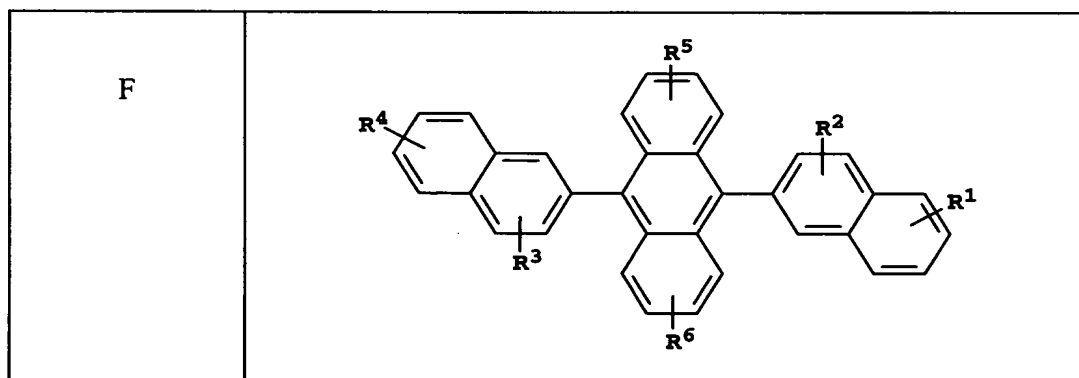
Z completes a heterocyclic nucleus containing at least two fused aromatic rings, at least one of which is an azole or azine ring. Additional rings, including both aliphatic and aromatic rings, can be fused with the two required

rings, if required. To avoid adding molecular bulk without improving on function the number of ring atoms is usually maintained at 18 or less.

Illustrative of useful chelated oxinoid compounds are the following:

- 5 CO-1: Aluminum trisoxine [alias, tris(8-quinolinolato)aluminum(III)]
- CO-2: Magnesium bisoxine [alias, bis(8-quinolinolato)magnesium(II)]
- CO-3: Bis[benzo {f}-8-quinolinolato]zinc (II)
- CO-4: Bis(2-methyl-8-quinolinolato)aluminum(III)-μ-oxo-bis(2-methyl-8-quinolinolato) aluminum(III)
- 10 CO-5: Indium trisoxine [alias, tris(8-quinolinolato)indium]
- CO-6: Aluminum tris(5-methyloxine) [alias, tris(5-methyl-8-quinolinolato) aluminum(III)]
- CO-7: Lithium oxine [alias, (8-quinolinolato)lithium(I)]
- CO-8: Gallium oxine [alias, tris(8-quinolinolato)gallium(III)]
- 15 CO-9: Zirconium oxine [alias, tetra(8-quinolinolato)zirconium(IV)]

Derivatives of 9,10-di-(2-naphthyl)anthracene (Formula F) constitute one class of useful host materials capable of supporting electroluminescence, and are particularly suitable for light emission of wavelengths longer than 400 nm, e.g., blue, green, yellow, orange or red.



20 wherein: R¹, R², R³, R⁴, R⁵, and R⁶ represent one or more substituents on each ring where each substituent is individually selected from the following groups:

Group 1: hydrogen, or alkyl of from 1 to 24 carbon atoms;

Group 2: aryl or substituted aryl of from 5 to 20 carbon atoms;

Group 3: carbon atoms from 4 to 24 necessary to complete a fused aromatic ring of anthracenyl; pyrenyl, or perylenyl;

Group 4: heteroaryl or substituted heteroaryl of from 5 to 24 carbon atoms as necessary to complete a fused heteroaromatic ring of furyl, thienyl, pyridyl,
5 quinolinyll or other heterocyclic systems;

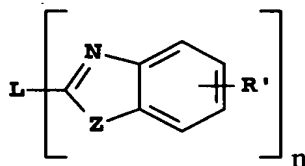
Group 5: alkoxyamino, alkylamino, or arylamino of from 1 to 24 carbon atoms; and

Group 6: fluorine, chlorine, bromine or cyano.

Illustrative examples include 9,10-di-(2-naphthyl)anthracene and 2-
10 *t*-butyl-9,10-di-(2-naphthyl)anthracene. Other anthracene derivatives can be useful as a host in the LEL, including derivatives of 9,10-bis[4-(2,2-diphenylethenyl)phenyl]anthracene.

Benzazole derivatives (Formula G) constitute another class of useful host materials capable of supporting electroluminescence, and are
15 particularly suitable for light emission of wavelengths longer than 400 nm, e.g., blue, green, yellow, orange or red.

G



Where:

n is an integer of 3 to 8;

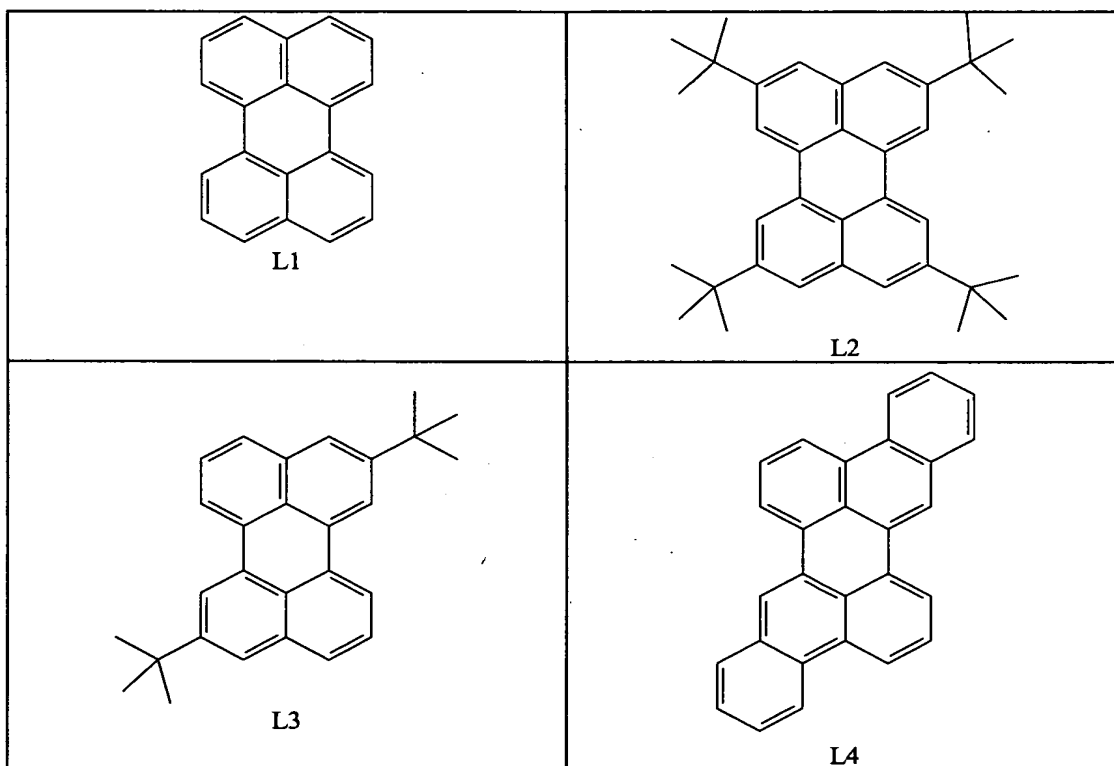
Z is O, NR or S; and

20 R and R' are individually hydrogen; alkyl of from 1 to 24 carbon atoms, for example, propyl, *t*-butyl, heptyl, and the like; aryl or hetero-atom substituted aryl of from 5 to 20 carbon atoms for example phenyl and naphthyl, furyl, thienyl, pyridyl, quinolinyll and other heterocyclic systems; or halo such as chloro, fluoro; or atoms necessary to complete a fused aromatic ring; and

25 L is a linkage unit consisting of alkyl, aryl, substituted alkyl, or substituted aryl, which conjugately or unconjugately connects the multiple benzazoles together. An example of a useful benzazole is 2, 2', 2''-(1,3,5-phenylene)tris[1-phenyl-1H-benzimidazole].

Styrylarylene derivatives as described in U.S. Patent 5,121,029 and JP 08333569 are also useful hosts for blue emission. For example, 9,10-bis[4-(2,2-diphenylethenyl)phenyl]anthracene and 4,4'-Bis(2,2-diphenylethenyl)-1,1'-biphenyl (DPVBi) are useful hosts for blue emission.

- 5 Useful fluorescent emitting materials include, but are not limited to, derivatives of anthracene, tetracene, xanthene, perylene, rubrene, coumarin, rhodamine, and quinacridone, dicyanomethylenepyran compounds, thiopyran compounds, polymethine compounds, pyrilium and thiapyrilium compounds, fluorene derivatives, perflanthene derivatives, indenoperylene derivatives,
- 10 bis(azinyl)amine boron compounds, bis(azinyl)methane compounds, and carbostyryl compounds. Illustrative examples of useful materials include, but are not limited to, the following:



L5

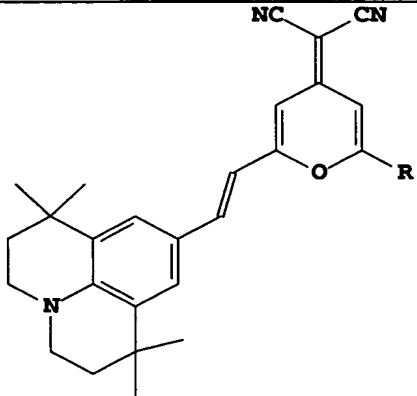
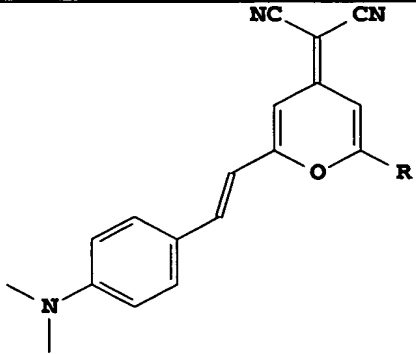
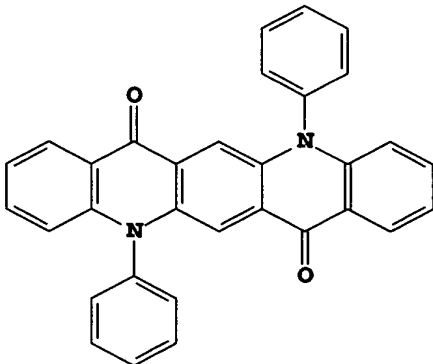
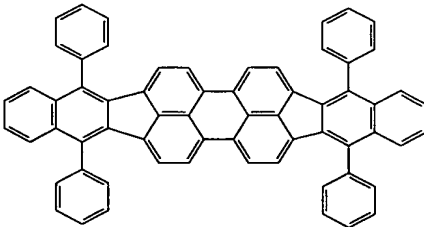
L6

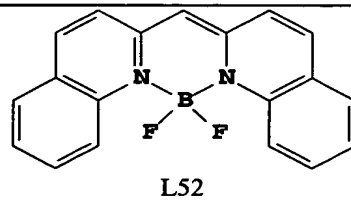
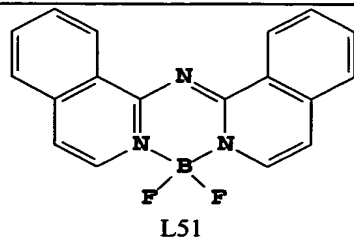
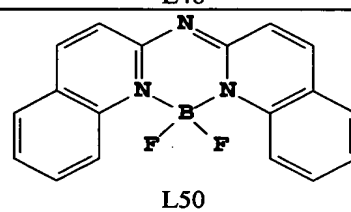
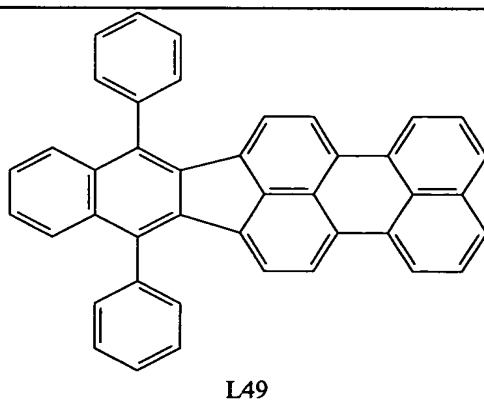
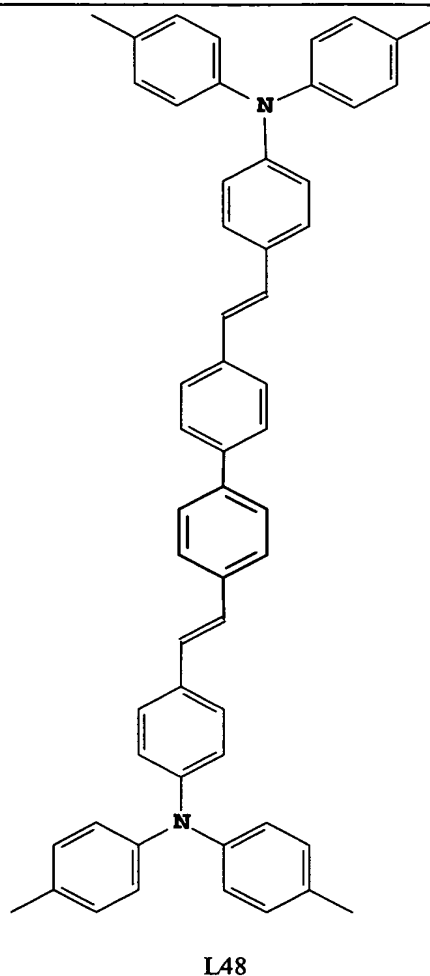
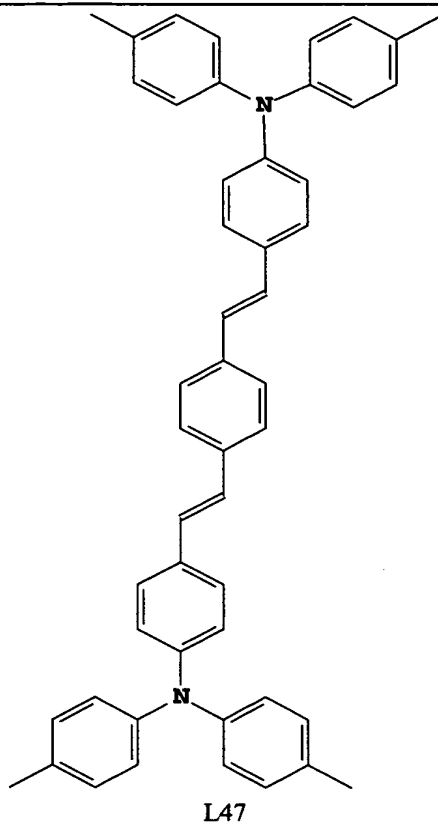
L7

L8

	<u>X</u>	<u>R1</u>	<u>R2</u>
L9	O	H	H
L10	O	H	Methyl
L11	O	Methyl	H
L12	O	Methyl	Methyl
L13	O	H	t-butyl
L14	O	t-butyl	H
L15	O	t-butyl	t-butyl
L16	S	H	H
L17	S	H	Methyl
L18	S	Methyl	H
L19	S	Methyl	Methyl
L20	S	H	t-butyl
L21	S	t-butyl	H
L22	S	t-butyl	t-butyl

	<u>X</u>	<u>R1</u>	<u>R2</u>
L23	O	H	H
L24	O	H	Methyl
L25	O	Methyl	H
L26	O	Methyl	Methyl
L27	O	H	t-butyl
L28	O	t-butyl	H
L29	O	t-butyl	t-butyl
L30	S	H	H
L31	S	H	Methyl
L32	S	Methyl	H
L33	S	Methyl	Methyl
L34	S	H	t-butyl
L35	S	t-butyl	H
L36	S	t-butyl	t-butyl

 <p>L37 L38 L39 L40</p> <p><u>R</u> phenyl methyl t-butyl mesityl</p>	 <p>L41 L42 L43 L44</p> <p><u>R</u> phenyl methyl t-butyl mesityl</p>
 <p>L45</p>	 <p>L46</p>



Electron-Transporting Layer (ETL)

Preferred thin film-forming materials for use in forming the electron-transporting layer **111** of the organic EL devices of this invention are metal chelated oxinoid compounds, including chelates of oxine itself (also commonly referred to as 8-quinolinol or 8-hydroxyquinoline). Such compounds help to inject and transport electrons and exhibit both high levels of performance and are readily fabricated in the form of thin films. Exemplary of contemplated oxinoid compounds are those satisfying structural formula (E), previously described.

Other electron-transporting materials include various butadiene derivatives as disclosed in US 4,356,429 and various heterocyclic optical brighteners as described in US 4,539,507. Benzazoles satisfying structural formula (G) are also useful electron transporting materials. Triazines are also known to be useful as electron transporting materials.

Other Useful Organic Layers and Device Architecture

In some instances, layers **109** through **111** can optionally be collapsed into a single layer that serves the function of supporting both light emission and electron transportation. Layers **110** and **111** may also be collapsed into a single layer that functions to block holes or excitons, and supports electron transportation. It also known in the art that emitting materials may be included in the hole-transporting layer, which may serve as a host. Multiple materials may be added to one or more layers in order to create a white-emitting OLED, for example, by combining blue- and yellow-emitting materials, cyan- and red-emitting materials, or red-, green-, and blue-emitting materials. White-emitting devices are described, for example, in EP 1 187 235, US 2002/0025419, EP 1 182 244, US 5,683,823, US 5,503,910, US 5,405,709, and US 5,283,182 and can be equipped with a suitable filter arrangement to produce a color emission.

This invention may be used in so-called stacked device architecture, for example, as taught in US 5,703,436 and US 6,337,492.

Deposition of Organic Layers

The organic materials mentioned above are suitably deposited by any means suitable for the form of the organic materials. In the case of small molecules, they are conveniently deposited through sublimation, but can be deposited by other means such as from a solvent with an optional binder to improve film formation. If the material is a polymer, solvent deposition is usually preferred. The material to be deposited by sublimation can be vaporized from a sublimator "boat" often comprised of a tantalum material, e.g., as described in US 6,237,529, or can be first coated onto a donor sheet and then sublimed in closer proximity to the substrate. Layers with a mixture of materials can utilize separate sublimator boats or the materials can be pre-mixed and coated from a single boat or donor sheet. Patterned deposition can be achieved using shadow masks, integral shadow masks (US 5,294,870), spatially-defined thermal dye transfer from a donor sheet (US 5,688,551, US 5,851,709 and US 6,066,357) and inkjet method (US 6,066,357).

Encapsulation

Most OLED devices are sensitive to moisture or oxygen, or both, so they are commonly sealed in an inert atmosphere such as nitrogen or argon, along with a desiccant such as alumina, bauxite, calcium sulfate, clays, silica gel, zeolites, alkaline metal oxides, alkaline earth metal oxides, sulfates, or metal halides and perchlorates. Methods for encapsulation and desiccation include, but are not limited to, those described in U.S. Patent No. 6,226,890. In addition, barrier layers such as SiO_x, Teflon, and alternating inorganic/polymeric layers are known in the art for encapsulation.

Optical Optimization

OLED devices of this invention can employ various well-known optical effects in order to enhance its properties if desired. This includes optimizing layer thicknesses to yield maximum light transmission, providing dielectric mirror structures, replacing reflective electrodes with light-absorbing electrodes, providing anti-glare or anti-reflection coatings over the display, providing a polarizing medium over the display, or providing colored, neutral

density, or color-conversion filters over the display. Filters, polarizers, and anti-glare or anti-reflection coatings may be specifically provided over the cover or as part of the cover.

Embodiments of the invention can provide advantageous features
5 such as higher luminous yield, lower drive voltage, and higher power efficiency. Embodiments of the organometallic compounds useful in the invention can provide a wide range of hues including those useful in the emission of white light (directly or through filters to provide multicolor displays).

The invention and its advantages can be better appreciated by the
10 following examples.

Triplet Energy Calculation Example 1

The triplet energy of compound Inv-1 was calculated using the
B3LYP/MIDI! method as implemented in the Gaussian98 (Gaussian, Inc.,
15 Pittsburgh, PA) computer program. The energies of the ground state, $E(\text{gs})$, and the lowest triplet state, $E(\text{ts})$, were calculated. The energy of each state was computed at the minimum-energy geometry for that state. The difference in energy between the two states was further modified by the following equation to give the triplet energy: $E(\text{t}) = 0.84 \cdot (E(\text{ts}) - E(\text{gs})) + 0.35$. This procedure was repeated for the
20 remaining compounds listed in Table 1. The triplet energies in eV and the wavelength which corresponds to the 0-0 transition (λ_{0-0}) are given in Table 1.

Table 1. Calculated Triplet Energies

Compound	Calculated $E(\text{t})$ (eV)	Calculated λ_{0-0} (nm)
Inv-1	2.09	593
Inv-6	2.23	556
Inv-11	2.55	486
Inv-16	2.81	441

25 As can be seen from the Table, complexes of the invention offer a wide range of hues and can be used to span the visible spectrum.

Synthetic Example 1: Preparation of Ligands.

2-Phenylimidazo[1,2-a]pyridine was prepared by the following procedure. A solution of 2-aminopyridine (9.4 g, 0.1 mol) and bromoacetophenone (19.9 g, 0.1 mol) in ethanol (75 mL) was heated to reflux for 2 h. The ethanol was
5 removed *in vacuo* and the residue redissolved in 100 mL ethyl acetate. The solution was washed with 1N NaHCO₃ (50 mL), followed by a water wash. The organics were dried over magnesium sulfate, filtered and the solvent removed *in vacuo*. Chromatography on silica with dichloromethane/ethyl acetate (90/10) eluent yielded the 2-phenylimidazo[1, 2-a]pyridine in 88% yield, mp 134°C. ¹H
10 NMR and mass spectra analysis confirmed the structure.

2-Phenylpyrazolo[1,5-a]pyridine was prepared by the following procedure. A solution of 2-(phenylethynyl)pyridine (3.2 g, 0.018 mol) in dichloromethane (20 mL) was cooled to 0°C in an ice bath. A solution of O-mesitylenesulfonylhydroxylamine in dichloromethane was added dropwise,
15 keeping the temperature below 5°C. The mixture was stirred for 30 minutes, then ethyl ether was added to precipitate a solid (5-7 g). The solid was filtered off, washed with ethyl ether and dried. The solid was re-dissolved in DMF and solid K₂CO₃ (4.5 g, 0.033 mol) was added in small portions. After stirring 2 h, water (100 mL) was added to the mixture, followed by extraction with dichloromethane.
20 The organics were dried over magnesium sulfate, filtered, and evaporated to an orange oil (2.3 g). Chromatography on silica with dichloromethane eluent yielded the 2-(phenylethynyl)pyridine in 83% yield, mp 110°C. ¹H NMR and mass spectra analysis confirmed the structure.

25 Synthetic Example 2: Preparation of Bis(2-phenylimidazo[1,2-a]pyridinato-N,C)iridium(III)(acetylacetonate) (Inv-24).

K₃IrBr₆ (2.75 g) and 2-phenylimidazo[1,2-a]pyridine (1.69 g) were placed in a 125 mL round-bottom flask. 2-Ethoxy ethanol (45 mL) and deionized water (15 mL) were added. The mixture was freeze-thaw degassed and refluxed 4
30 hrs under nitrogen atmosphere. After cooling, the resulting precipitate was filtered in air and washed with ethanol and water to give 1.975 g of yellow-brown powder.

The mass spectrum was consistent with the formulation tetrakis(2-phenylimidazo[1,2-a]pyridinato)(di- μ -bromo)diiridium(III). This material was used in the next step without further purification.

Tetrakis(2-phenylimidazo[1,2-a]pyridinato)(di- μ -bromo)diiridium(III) (0.654 g) and sodium acetylacetonate hydrate (0.417 g) were placed in a 100 mL round bottom flask. 1,2-Dichloroethane (30 mL) was added. The mixture was freeze-thaw degassed and then refluxed under nitrogen 20 h. After cooling, the reaction solution was filtered in air. The product was precipitated by concentrating and adding a few drops of hexane. The yellow-brown powder was filtered and dried (0.634 g) to afford bis(2-phenylimidazo[1,2-a]pyridinato-N,C)iridium(III)(acetylacetonate) (Inv-24), which emitted green light in solution. The product was characterized by ^1H NMR spectroscopy.

Device Example 1

An EL device (Device 1) satisfying the requirements of the invention was constructed in the following manner:

A glass substrate coated with an 85-nm layer of indium-tin oxide (ITO) as the anode was sequentially ultrasonicated in a commercial detergent, rinsed in deionized water, degreased in toluene vapor and exposed to ultraviolet and ozone for several minutes.

1. A glass substrate coated with an 85-nm layer of indium-tin oxide (ITO) as the anode was sequentially ultrasonicated in a commercial detergent, rinsed in deionized water, degreased in toluene vapor and exposed to ultraviolet and ozone for several minutes.
2. Over the ITO was deposited a 60-nm PEDOT hole-injecting layer (HIL) by spin coating an aqueous solution of PEDOT/PSS (1.3% in water, Baytron® P from H.C. Stark, Inc.) under controlled spinning rate of 1750 rpm to obtain the desired layer thickness of about 60 nm and then annealing the coating on a heated metal block in air at 120 °C for about 10 min.
3. A light-emitting layer (LEL) of poly(9-vinylcarbazole) host material (PVK, Aldrich Chemical Co., used as received, typical M_w 63,000, typical M_n

19,000) was then fabricated. Compound Inv-24 was combined with the host, PVK, in an amount of 4% by weight relative to the PVK. The mixture was dissolved in chlorobenzene (2% solids), filtered, and then deposited onto the hole-injecting layer of PEDOT by spin casting under a controlled spinning rate of 1500 rpm to obtain the desired layer thickness of about 66 nm and then baking the coating in an oven at 120 °C for 20 min.

4. On top of LEL was deposited a 1.5-nm layer formed of cesium fluoride (CsF) by evaporative vacuum deposition.

5. On top of the CsF layer was deposited a 200-nm cathode layer formed of a 10:1 atomic ratio of Mg and Ag by evaporative vacuum deposition.

The above sequence completed the deposition of the EL device. The device was then hermetically packaged in a dry glove box for protection against ambient moisture and oxygen.

Device Example 2 (Comparative).

A second device (Device 2) was fabricated in an identical manner to Device 1, except that the light-emitting compound Inv-24 was omitted from the chlorobenzene solution of the LEL host compound.

The device cells thus prepared were tested for luminance and CIE (Commission Internationale de L'Eclairage) color coordinates at an operating current of 100 mA/cm². The comparison Device 2 containing no phosphorescent organometallic compound showed the emission from PVK having a peak emission at 416 nm and CIE(X,Y) of (0.21,0.14), while the Device 1 comprising the Inv-24 compound showed the emission at peak wavelength of 520 nm and CIE (X,Y) of (0.37, 0.58). The inventive compound gave a desirable green hue.

The entire contents of the patents and other publications referred to in this specification are incorporated herein by reference. The invention has been described in detail with particular reference to certain preferred embodiments thereof, but it will be understood that variations and modifications can be effected within the spirit and scope of the invention.

PARTS LIST

101	Substrate
103	Anode
105	Hole-Injecting layer (HIL)
107	Hole-Transporting layer (HTL)
109	Light-Emitting layer (LEL)
110	Hole-blocking layer (HBL)
111	Electron-Transporting layer (ETL)
113	Cathode